What is claimed is:

1   1. A computer-implemented method of simulating the corneal strain relationship

2   produced by patient specific corneal deformation in response to a physical change in

3   the cornea, comprising the steps of:

4   (a) measuring the topography of a portion of the patient's eye using a topography

5   measuring device to produce patient specific x,y,z coordinates for a number of

6   patient specific data points of the surface of the patient's eye;

7   (b) storing in a storage device a mathematical analysis model of the patient's eye, the

8   model including a number of nodes, the connectivities of which define a plurality

9   of elements;

10   (c) determining a value representing intraocular pressure in the patient's eye and

11   assigning a strain value to each element;

12   (d) representing an insertion in the mathematical analysis model by assigning new

13   values to the topography of the portion of the patient's eye surrounding the

14   insertion corresponding to the size, shape, and thickness of the insertion and a

15   value of the modulus of elasticity to elements surrounding the insertion computed

16   from the value determined in step (c); and

17   (e) using the mathematical analysis model to compute new values of the patient

18   specific x,y,z coordinates and therefrom, new strain relationships resulting from

19   the insertion at each of the nodes, respectively.

1   2. A computer-implemented method of simulating the corneal strain relationship

2   produced by patient specific corneal deformation in response to a physical change in

3   the cornea, comprising the steps of:

4   (a) measuring the topography of a portion of the patient's eye using a topography

5   measuring device to produce patient specific x,y,z coordinates for a large number

6   of patient specific data points of the surface of the patient's eye;

7   (b) storing in a storage device operably associated with a computer system for

8   implementing the computer-implemented method, a mathematical analysis model

9   of the patient's eye, the model including a number of nodes, the connectivities of

10   which define a plurality of elements;

11   (c) determining a value representing intraocular pressure in the patient's eye and

12   assigning a strain value to each element;

13   (d) representing an insertion in the mathematical analysis model by changing the z

14   coordinate of the nodes surrounding the insertion and representing the effect of

15   the insertion by means of a plurality of nonlinear spring elements each connecting

16   an insertion-bounding node to an adjacent node, respectively each of the plurality

17   of nonlinear spring elements having a load deflection curve based upon size,

18   shape, and thickness of the insertion and the value obtained from step (c); and

19   (e) using the mathematical analysis model to compute new values of the patient

20   specific x,y,z coordinates and therefrom, new strain relationships resulting from

21   the insertion at each of the nodes, respectively.

1   3. The computer-implemented method of claim 2 including establishing at least one

2   vision objective for the patient's eye, wherein step (e) includes comparing the

3   simulated strain relationship within the cornea with a vision objective to determine if

4   the insertion results in the vision objective being met, and, if the vision objective is

5   not met, modifying the insertion and/or adding another changes to the cornea in the

6   mathematical analysis model and repeating step (e) to determine if the at least one

7   vision objective is met.

1   4. A computer-implemented method of simulating the corneal strain relationship

2   produced by patient specific corneal deformation in response to a physical change in

3   the cornea, comprising the steps of:

4   (a) measuring the topography of a portion of the patient's eye using a topography

5   measuring device to produce patient specific x,y,z coordinates for a number of

6   patient specific data points of the surface of the patient's eye;

7   (b) storing in a storage device a mathematical analysis model of the patient's eye, the

8   model including a predetermined number of nodes, the connectivities of which

9   define a plurality of elements;

10   (c) determining a value representing intraocular pressure in the patient's eye and

11   assigning a strain value to each element;

12   (d) representing a thermal shrinkage of a portion of the cornea in the mathematical

13   analysis model by assigning at least one of reduced values of the thickness and a

14   reduced value of the modulus of elasticity to elements corresponding to the

15   thermally shrunk portion of the cornea; and

16   (e) using the mathematical analysis model to compute new values of the patient

17   specific x,y,z coordinates and therefrom, new strain relationships resulting from

18   the thermal shrinkage at each of the nodes, respectively.

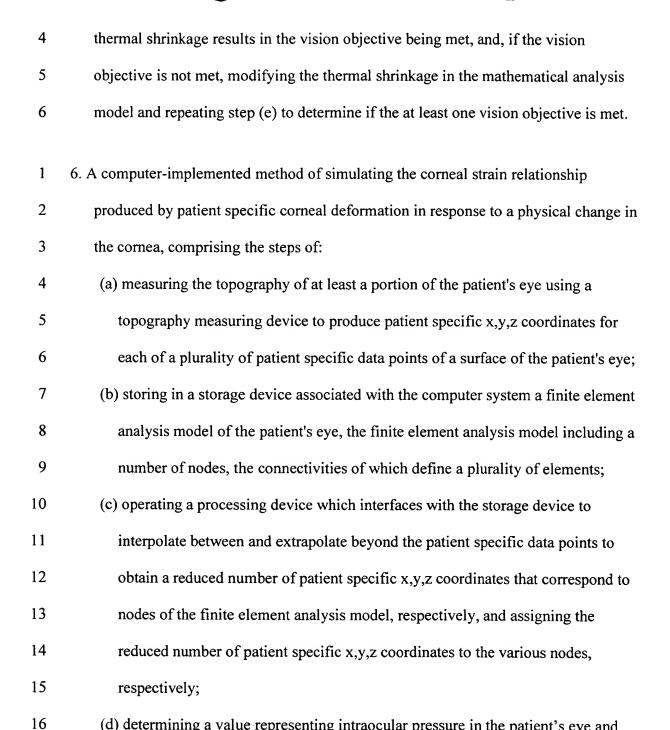1   5. The computer-implemented method of claim 4 including establishing at least one

2   vision objective for the patient's eye, wherein step (e) includes comparing the

3   simulated deformation of the cornea with the vision objective to determine if the

4   thermal shrinkage results in the vision objective being met, and, if the vision

5   objective is not met, modifying the thermal shrinkage in the mathematical analysis

6   model and repeating step (e) to determine if the at least one vision objective is met.

1   6. A computer-implemented method of simulating the corneal strain relationship

2   produced by patient specific corneal deformation in response to a physical change in

3   the cornea, comprising the steps of:

4   (a) measuring the topography of at least a portion of the patient's eye using a

5   topography measuring device to produce patient specific x,y,z coordinates for

6   each of a plurality of patient specific data points of a surface of the patient's eye;

7   (b) storing in a storage device associated with the computer system a finite element

8   analysis model of the patient's eye, the finite element analysis model including a

9   number of nodes, the connectivities of which define a plurality of elements;

10   (c) operating a processing device which interfaces with the storage device to

11   interpolate between and extrapolate beyond the patient specific data points to

12   obtain a reduced number of patient specific x,y,z coordinates that correspond to

13   nodes of the finite element analysis model, respectively, and assigning the

14   reduced number of patient specific x,y,z coordinates to the various nodes,

15   respectively;

16   (d) determining a value representing intraocular pressure in the patient's eye and

17   assigning a strain value to each element;

18   (e) representing a first insertion in the finite element analysis model by representing

19   the thickness of the insertion by changing the z coordinate of elements

20   surrounding the insertion and representing the change in the corneal elasticity

21   caused by the of the first insertion by means of a plurality of nonlinear spring

22   elements having load deflection curves based upon the at least one material

23   property value determined in step (d) and insertion thickness, each nonlinear

24   spring element connecting an insertion affected node to an adjacent node,

25   respectively, by shell modeling;

26   (f) using the finite element analysis model to compute at each of the nodes, new

27   values of the patient specific x,y,z coordinates and therefrom, new strain

28   relationships resulting from the insertion at each of the nodes; and

29   (g) displaying the strain relationships at the nodes having the computed patient

30   specific x,y,z coordinates to show the simulated resulting deformation of the

31   cornea.

1   7. The computer-implemented method of claim 1 including establishing at least one

2   vision objective for the patient's eye, said at least one vision objective being selected

3   from the group consisting of visual acuity, duration of treatment, absence of side

4   effects, low light vision, astigmatism, contrast and depth perception, and storing

5   vision objective information in the storage device, wherein step (f) includes

6   comparing the simulated deformation of the cornea with the vision objective

7   information to determine if the insertion results in the vision objective being met.

1   8. The computer-implemented method of claim 7 including, if the vision objective is not

2   met, modifying the first insertion and/or adding a second insertion in the finite

3   element analysis model similar to the first insertion, and repeating step (f) to

4   determine if the vision objective is met.

1   9. The method of claim 8 wherein step (c) includes executing the finite element analysis

2   model so as to equalize the strain relationship of the surface of the patient's eye

3   represented in the finite element analysis model.

1   10. The computer-implemented method of claim 9 including measuring the thickness of

2   various points of the cornea and/or sclera and assigning values of the measured

3   thicknesses to each element of the finite element analysis model, respectively, before

4   step (f).

1   11. The computer-implemented method of claim 9 including modeling a thermal

2   shrinkage of the cornea in the finite element analysis model by assigning at least one

3   of reduced values of the thickness and a reduced value of the modulus of elasticity to

4   elements corresponding to the thermally shrunk portion of the cornea, respectively.

1   12. The computer-implemented method of claim 9 wherein the first insertion is a torous

2   shaped insertion.

1   13. The computer-implemented method of claim 9 including assigning values of material

2   constants of the eye, including Poisson's ratio, modulus of elasticity, and shear

3   modulus, to each element of the finite element analysis model.

1   14. The computer-implemented method of claim 8 wherein the modifying includes

2   executing a nonlinear programming computer program to determine how much to

3   modify the number of insertion, the shapes of the insertions, and the thickness of the

4   various insertions.

1 15. The computer-implemented method of claim 7 wherein establishing the at least one

2   vision objective includes providing an initial set of surface curvatures for the cornea,

3   the computer-implemented method including computing simulated post-operative

4   curvatures from the new values of patient specific x,y,z coordinates computed in step

5   (f) and comparing the simulated post-operative curvatures with the surface curvatures

6   of the initial set to determine if the at least one vision objective is met.

1 16. The method of claim 7 wherein each element of the finite element analysis model is

2   an eight-node element, and wherein a boundary condition of the finite element

3   analysis model is that a base portion of the finite element analysis model is stationary.

1 17. The method of claim 8 including assigning substantially different measured values of

2   strain to elements of cornea portions and sclera portions of the finite element analysis

3.   model.

1 18. The computer-implemented method of claim 1 wherein step (c) includes executing a

2   cubic spline computer program to obtain the reduced number of patient specific x,y,z

3   coordinates according to an equation $z=ax^3+bx^2+cx+d$ which has been fit to the

4   measured patient specific data points of step (a), x being a distance from an apex axis

5   of the patient's eye.

1 19. The computer-implemented method of claim 8 including selecting at least one vision

2   objective for each patient which produces a simulated multi-focal configuration of the

3   cornea.

1   20. A computer-implemented method of simulating patient specific corneal deformation

2   as a result of a corneal thermal shrinkage on a patient's eye, comprising the steps of:

3   (a) measuring the topography of a portion of the patient's eye using a topography

4   measuring device to produce patient specific x,y,z coordinates for a number of

5   patient specific data points of a surface of the patient's eye;

6   (b) storing in a storage device associated with a computer system used for the

7   computer-implemented method, a finite element analysis model of the patient's

8   eye, the finite element analysis model including a predetermined number of

9   nodes, the connectivities of which define a plurality of elements,

10   (c) operating a processing device operatively associated with the computer system to

11   interpolate between and extrapolate beyond the patient specific data points to

12   obtain a reduced number of patient specific x,y,z coordinates that correspond to

13   nodes of the finite element analysis model, respectively, and assigning the x,y,z

14   coordinates to the various nodes, respectively;

15   (d) determining a value representing intraocular pressure in the patient's eye and

16   assigning a strain value to each element;

17   (e) representing a thermal shrinkage of a portion of the cornea in the mathematical

18   analysis model by assigning at least one of reduced values of the thickness and a

19   reduced value of the modulus of elasticity to elements corresponding to the

20   thermally shrunk portion of the cornea, respectively;

21   (f) using the finite element analysis model, computing new values of the patient

22   specific x,y,z coordinates at each of the nodes to simulate deformation of the

23   cornea resulting from the proposed thermal shrinkage; and

24   (g) operating the processing device to display the computed patient specific x,y,z

25   coordinates to show the simulated deformation of the cornea.

1   21. A computer-implemented method of determining change of a cornea of a patient's eye

2   as a result of an thermal shrinkage on the cornea, the computer-implemented method

3   including the steps of:

4   (a) storing in a storage device operatively associated with a computer system for

5   implementing the computer-implemented method, a finite element analysis model

6   of a patient's eye, the finite element analysis model including a number of nodes,

7   the connectivities of which define a plurality of elements;

8   (b) applying a known external pressure to the patient's eye and then measuring the

9   topography of a portion of the patient's eye using a topography measuring device

10   to produce patient specific x,y,z coordinates for a number of patient specific data

11   points of the pressure-deformed surface of the patient's eye and then remapping

12   the topography by backcalculating the data;

13   (c) operating a processing device operatively associated with the computer system to

14   interpolate between and extrapolate beyond the patient specific data points to

15   obtain a reduced number of patient specific x,y,z coordinates that correspond to

16   the nodes of the finite element analysis model, respectively, and assigning the

17   reduced number of patient specific x,y,z coordinates to the various nodes

18   respectively, and assigning the value of the external pressure to elements of the

19   finite element analysis model corresponding to locations of the patient's eye to

20   which the external pressure is applied in step (b);

21 (d) determining a value representing intraocular pressure in the patient's eye and

22 assigning a strain value to each element;

23 (e) assigning initial values of the strain to each element, respectively, of the finite

24 element analysis model;

25 (f) using the finite element analysis model, computing new values of the patient

26 specific x,y,z coordinates at each of the nodes to simulate deformation of the

27 cornea resulting from the external pressure and the intraocular pressure for the

28 initial values of the strain;

29 (g) comparing the new values of the patient specific x,y,z coordinates computed in

30 step (f) with the patient specific x,y,z coordinates recited in step (c);

31 (h) operating the processing device to modify values of the strain of the finite

32 element analysis model, respectively, if the comparing of step (g) indicates a

33 difference between the patient specific x,y,z coordinates obtained in step (c) and

34 the patient specific x,y,z coordinates computed in step (f) exceeds a

35 predetermined criteria;

36 (i) repeating steps (f) through (h) until final values of the strain are obtained;

37 (j) representing a thermal shrinkage of a portion of the cornea in the mathematical

38 analysis model by assigning at least one of reduced values of the thickness and a

39 reduced value of the modulus of elasticity to elements corresponding to the

40 thermally shrunk portion of the cornea, respectively;

41 (k) using the finite element analysis model, computing new values of the patient

42 specific x,y,z coordinates at each of the nodes to simulate deformation of the

43 cornea resulting from the proposed ablation;

44   (l) comparing the simulated deformation of the cornea with at least one pre-

45   established vision objective for the patient's eye, said at least one pre-established

46   vision objective being selected from the group consisting of visual acuity,

47   duration of treatment, absence of side effects, low light vision, astigmatism,

48   contrast and depth perception, to determine if the ablation results in the vision

49   objective being met; and

50   (m) if the vision objective is not met, modifying the proposed thermal shrinkage in

51   the finite element analysis model and repeating steps (j) through (l) until the at

52   least one pre-determined vision objective is met.

1   22. A computer-implemented method of simulating change of a cornea of patient specific

2   patient's eye as a result of a proposed insertion on the cornea, the computer-

3   implemented method including the steps of;

4   (a) storing in a storage device operatively associated with a computer system used

5   for the computer-implemented method, a finite element analysis model of a

6   patient's eye, the finite element analysis model including a number of nodes, the

7   connectivities of which define a plurality of elements;

8   (b) applying a known external pressure to the patient's eye and then measuring the

9   topography of a portion of the patient's eye under the influence of the externally

10   applied pressure using a topography measuring device to produce patient specific

11   x,y,z coordinates for a number of patient specific data points of the surface of the

12   patient's eye and then remapping the topography by backcalculating the data;

13   (c) operating a processing device associated with the computer system to interpolate

14   between and extrapolate beyond the patient specific data points to obtain a

15   reduced number of patient specific x,y,z coordinates that correspond to the nodes

16   of the finite element analysis model, respectively, and assigning the reduced

17   number of patient specific x,y,z coordinates to the various nodes respectively, and

18   assigning the value of the external pressure to elements of the finite element

19   analysis model corresponding to locations of the patient's eye to which the

20   external pressure is applied in step (b);

21   (d) determining a value representing intraocular pressure in the patient's eye and

22   assigning a strain value to each element;

23   (e) assigning initial values of the strain to each element, respectively, of the finite

24   element analysis model;

25   (f) using the finite element analysis model, computing new values of the patient

26   specific x,y,z coordinates at each of the nodes to simulate deformation of the

27   cornea resulting from the external pressure and the intraocular pressure for the

28   initial values of the strain;

29   (g) comparing the new values of the patient specific x,y,z coordinates computed in

30   step (f) with the patient specific x,y,z coordinates recited in step (c);

31   (h) operating the processing device to modify values of the strain of the elements of

32   the finite element analysis model respectively, if the comparing of step (g)

33   indicates a difference between the patient specific x,y,z coordinates obtained in

34   step (c) and the patient specific x,y,z coordinates computed in step (f) exceeds a

35   predetermined criteria;

36   (i) repeating steps (f) through (h) until a final value of the strain is obtained;

37   (j) representing the insertion in the finite element analysis model, by shell modeling,

38   by representing the thickness of the insertion by changing the z coordinate of

39   elements surrounding the insertion and representing the change in the corneal

40   elasticity caused by the of the first insertion by means of a plurality of nonlinear

41   spring elements having load deflection curves based upon the at least one material

42   property value determined in step (i) and insertion thickness, each of the plurality

43   of nonlinear spring elements connecting an insertion-bounding node to an

44   adjacent node, respectively;

45   (k) using the finite element analysis model, computing new values of the patient

46   specific x,y,z coordinates at each of the nodes to simulate deformation of the

47   cornea resulting from the insertion and the intraocular pressure;

48   (l) comparing the simulated deformation of the cornea with at least one pre-

49   established vision objective for the patient's eye to determine if the insertion

50   results in the at least one vision objective being met; and

51   (m) if the vision objective is not met, modifying the insertion in the finite element

52   analysis model and repeating steps (j) through (l) until the vision objective is met.